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Average Forecast Errors Using MM5 and WRF Over Complex Terrain: Utah, July/August 2003 and January/February 2004

by Barbara Sauter and Teizi Henmi

ARL-MR-597 October 2004

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Army Research Laboratory
White Sands Missile Range, NM 88002-5501

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14. ABSTRACT
This report documents average weather forecast errors associated with two mesoscale models run over northern Utah during two months in the summer (2003) and two months in the winter (2004). The models used were the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (MM5) and the Weather Research and Forecast (WRF) model, version 1.3. The forecast values of surface temperature, dew-point temperature, wind speed, and wind direction were compared to station observation data obtained through the University of Utah MesoWest Cooperative.

15. SUBJECT TERMS
Weather Forecast Errors; Forecast Accuracy; WRF; MM5; Utah MesoWest

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Summary

Computer models continue to be developed and modified to provide more accurate weather forecasts. The Army is particularly concerned with the ability of forecast models to provide appropriate weather data for regional scales including complex terrain. This study investigated the performance of two models run over the widely varying topography of northern Utah. Twenty-four hourly forecasts were generated daily for most days for two winter and two summer months. One of the models used was the Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model Version 5 (MM5), which was run in a triple nest. The other model used was a non-nested version of the Weather Research and Forecast (WRF) model. The model forecasts for surface values of temperature, dew-point temperature, and wind components were compared to surface observations from various observation sites. The average errors found through these comparisons were typically higher than desired, particularly for dew-point temperatures, as documented in this report. Additional analyses will be performed on some specific station results from the data obtained in this study, but future evaluations will be based on a more recent version of the WRF model, which includes a nesting capability.

1. Introduction

Atmospheric scientists may choose from a variety of numerical weather prediction computer models. The Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5) provides regional-scale forecasts for both military and civilian users (*1*). A new model, called the Weather Research and Forecast (WRF), is being developed by NCAR, the National Oceanic and Atmospheric Administration, and several universities (*2*). The WRF is meant to improve on current regional forecasting capabilities, as well as to provide a tool useful to both operational weather forecasters and researchers.

Previous studies examined MM5 performance over Utah during December 2002 through February 2003 (*3, 4*). In order to become familiar with running the first version of the WRF, it was run over the same area for most dates in July and August 2003 and January and February 2004. The MM5 was also run for the same location and dates. However, this study is not meant to be a comparison between the two models. The version of WRF used did not provide nesting capabilities, while the MM5 output was from the inner nest of three nests.

This report provides a preliminary summary of the average errors calculated by comparing the forecast models' output of basic parameters with the surface observations available from the University of Utah MesoWest Cooperative (*5*). The WRF temperature, humidity, and wind forecast errors, in general, were quite large. This was also true for the MM5 forecasts, which showed average temperature and dew-point temperature errors significantly larger than those found in the previous year's study.

2. Methodology

Both the MM5 and WRF models were initialized using the Global Forecast System (GFS) model (*6*). Model runs were initialized at 1800 Zulu Time for 28 days in July 2003, 26 days in August 2003, 28 days in January 2004, and 29 days in February 2004. The models provided hourly output covering a 30-hour period, of which the initial 6 hours were used for spin-up purposes and the remaining 24 hours were used for validations.

The model domains incorporated complex terrain in northern Utah (fig. 1). The MM5 runs consisted of an outer nest based on 45-km grid point spacing, a middle nest with 15-km spacing, and an inner nest with 5-km spacing. The inner nest contained 85-by-85 grid points covering a 420 km-by-420 km area, and only these results were used for the MM5 validations. The WRF runs were performed without nesting, since the initial version of the WRF did not provide this capability. A larger area was selected to provide the WFR output, consisting of a 5-km grid point spacing for 101-by-101 grid points covering 500 km by 500 km. The stations used for WRF validations were the same as the ones used for the MM5 validations. The larger WRF area was chosen so that no validations would need to be performed near the boundaries of the WRF domain, where the shortcomings due to not having a nested model would be expected to be greatest.

Figure 1. The MM5 model domain (inner box in blue) and the WRF model domain (outer box in purple).

For each model, forecasts of temperature, dew-point temperature, and *u*- and *v*-wind components were interpolated to surface station locations. These forecast values were then compared to hourly observations provided through the Utah MesoWest Cooperative. Approximately 40 to 70 stations were available for most hours. The observed data were transferred without the data flags highlighting questionable observations, and the station location density was not uniform, with many stations located in the Salt Lake City, UT, vicinity. Therefore, the average error statistics presented in the next section may be skewed by bad observations and by a particularly good or bad forecast being multiplied by several stations in the same vicinity.

3. Results

In general the average forecast errors found in this study are significantly higher than expected. These poor results cannot be solely attributed to the non-nested version 1.3 of the WRF model, since the MM5 average forecast errors were almost as high, or even higher, than the WRF errors. The MM5 errors found in the 2004 winter months were substantially higher than those seen in a previous study based on 2003 winter months. That study did not include any model runs for the summer months. The following sections document the overall results for the basic weather parameters.

3.1 Temperature Forecast Errors

The average temperature forecast errors are summarized in table 1.

Table 1. Average temperature forecast errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (°C)	1.3	3.2	0.1	2.9	-1.0
Absolute Error (°C)	2.5	3.7	2.9	3.6	2.8
RMSE (°C)	3.4	5.3	3.7	4.9	3.6
Correlation Coefficient	.83	.69	.86	.72	.91
Number of Points	58000	54000	72000	55000	75000

NOTE: RMSE = root mean square error.

The winter temperature forecasts displayed a warm bias around 3 °C in both the MM5 and the WRF runs. The summer results were better, with very little bias in the MM5 forecasts and a 1 °C cold bias in the WRF forecasts. The absolute error amounts were very similar for both models: around 3.5 °C in the winter and 3.0 °C in the summer.

Figure 2 shows the variation in the WRF results between the two months used in each seasonal summary.

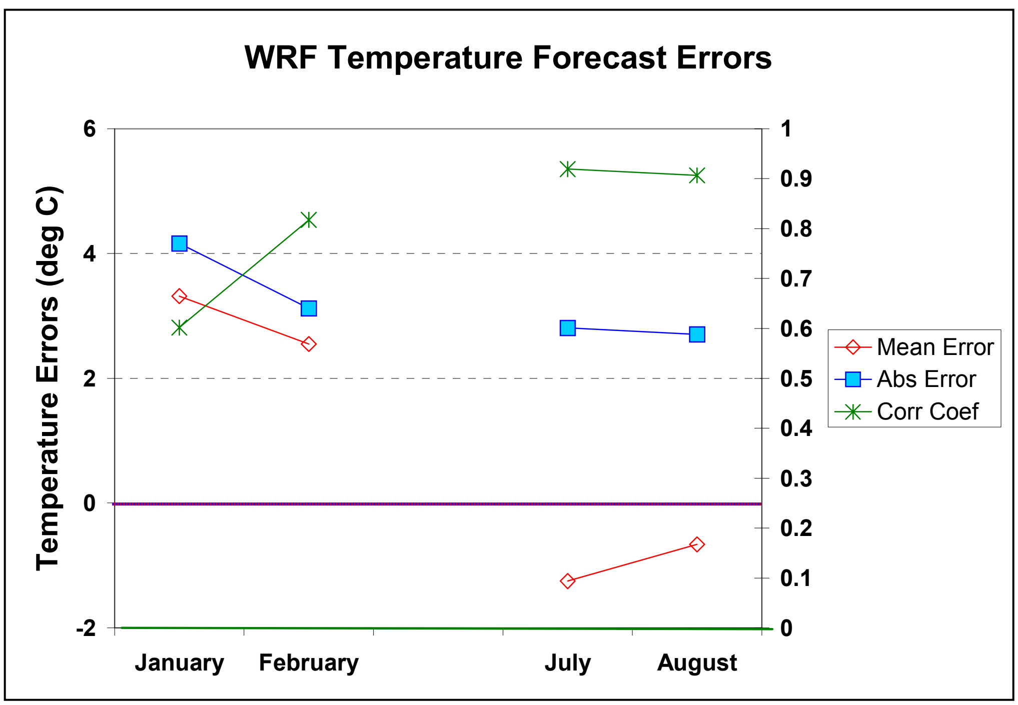

Figure 2. WRF temperature forecast errors (left axis) and correlation coefficients (right axis) by month.

Averaging errors over many data points conceals a great deal of variation associated with particular times and places, but the amount of data involved necessitates summarization. Another way to look at the forecast errors is by forecast time. The WRF temperature errors, averaged for the winter model runs by forecast hour, are shown in figure 3. Forecast hour 0 is at 5 p.m., local Mountain Standard Time. The temperature errors are uniformly around 3.5 °C for hours 0 through 15, and then climb to 4.5 °C by hour 21, before decreasing again in hours 22 and 23. Looking at the average temperature errors by hour, averaged for the eight individual weeks included in the winter data, all but two of the weeks showed this increase in forecast error in the later hours. A similar trend is also seen in the MM5 forecasts.

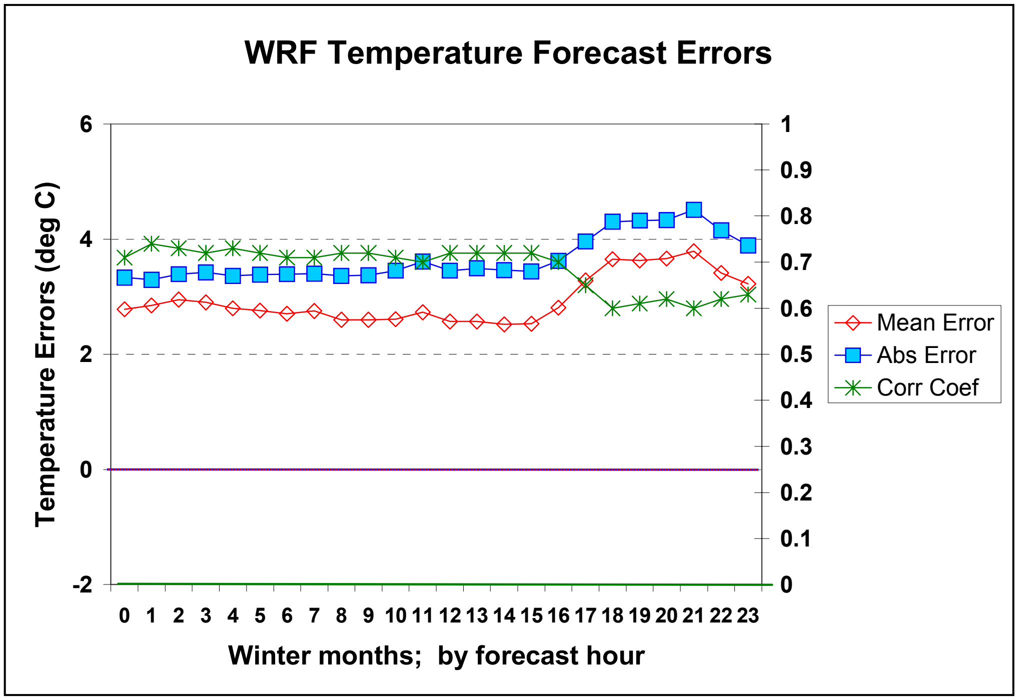

Figure 3. WRF temperature forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the winter model runs.

The WRF temperature errors by forecast hour for the summer model runs did not exhibit this maximum error at hour 21 (see fig. 4). The primary difference between the MM5 and WRF temperature errors in the summer months is highlighted in figure 5, which shows the MM5 bias switching from too cold during the daytime hours to too warm during the night. The equivalent WRF bias is also too cold during the day, but stays slightly cold during the night.

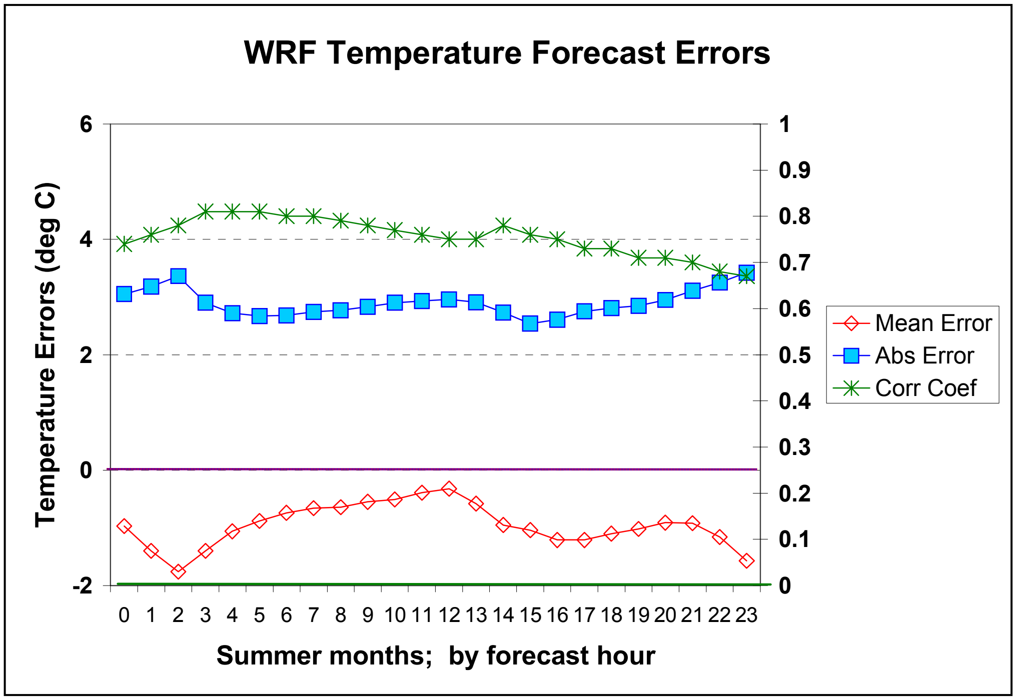

Figure 4. WRF temperature forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the summer model runs.

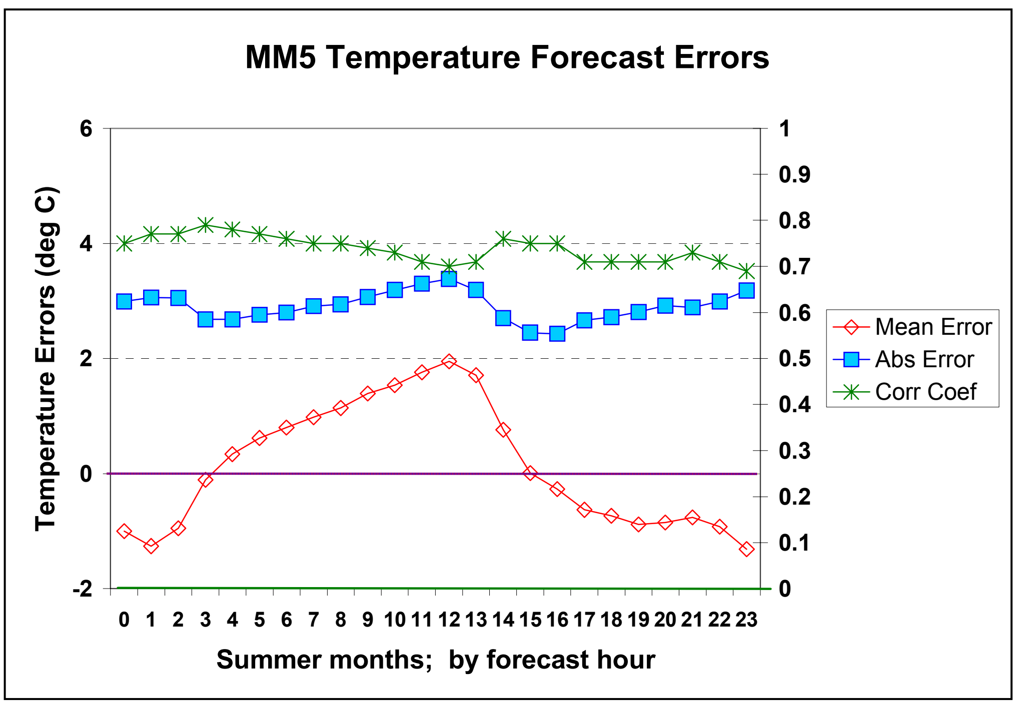

Figure 5. MM5 temperature forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the summer model runs.

3.2 Dew-Point Temperature Forecast Errors

The average dew-point temperature forecast errors are summarized in table 2.

Table 2. Average dew-point temperature errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (°C)	1.4	2.5	7.4	4.1	7.9
Absolute Error (°C)	2.9	3.4	7.5	4.5	8.1
RMSE (°C)	4.2	5.2	9.4	6.2	10.0
Correlation Coefficient	.73	.69	.50	.66	.42
Number of Points	58000	54000	72000	53000	71000

The seasonal averages again obscure the differences between the two months in each season, as seen in figure 6.

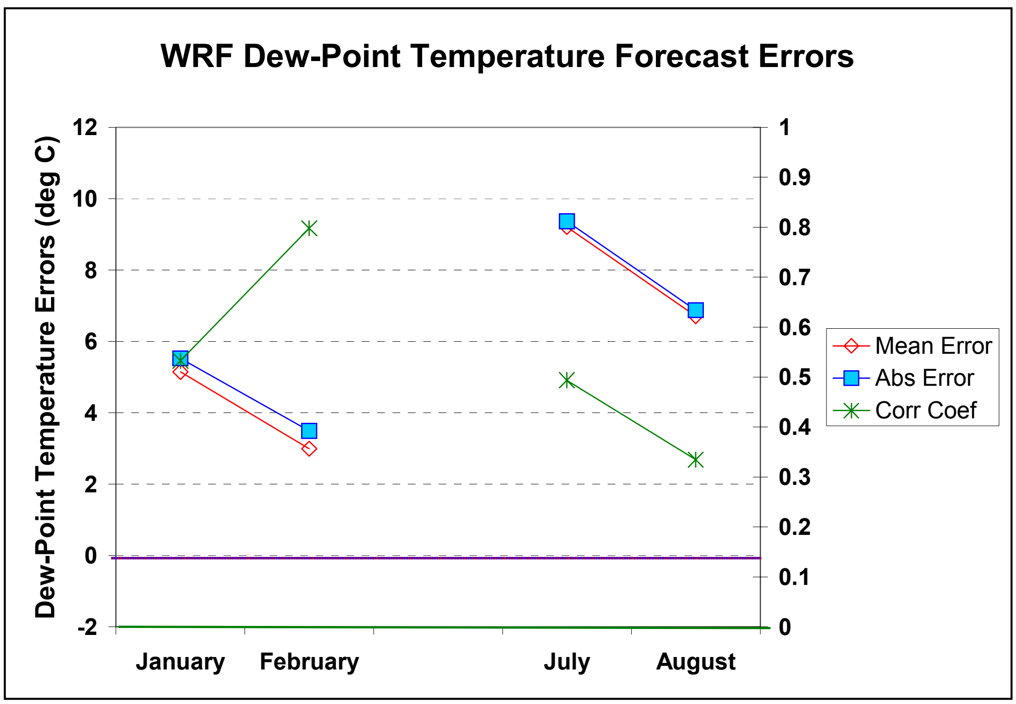

Figure 6. WRF dew-point temperature errors (left axis) and correlation coefficients (right axis) by month.

The average dew-point temperature errors by forecast hour for the winter runs decreased in hours 17-23, when the temperature errors had increased (fig. 7). The summer runs included huge errors in dew-point temperature forecasts, with a maximum average error of 12 °C at forecast

hour 2 (fig. 8). The MM5 model runs reflected similar trends, but not to the extremes produced by the WRF.

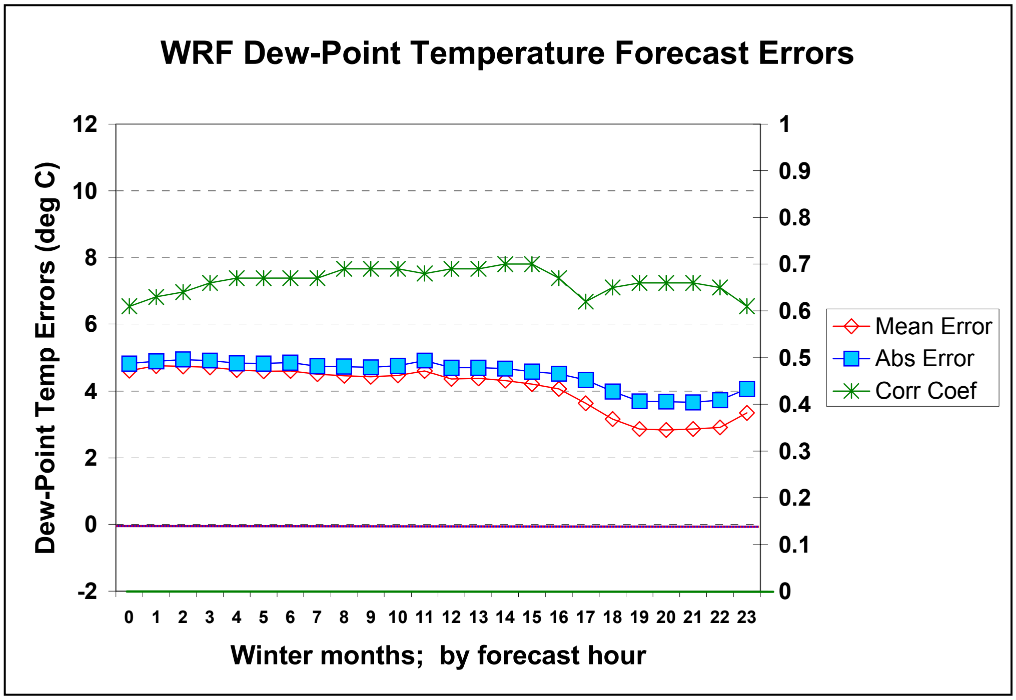

Figure 7. WRF dew-point temperature forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the winter model runs.

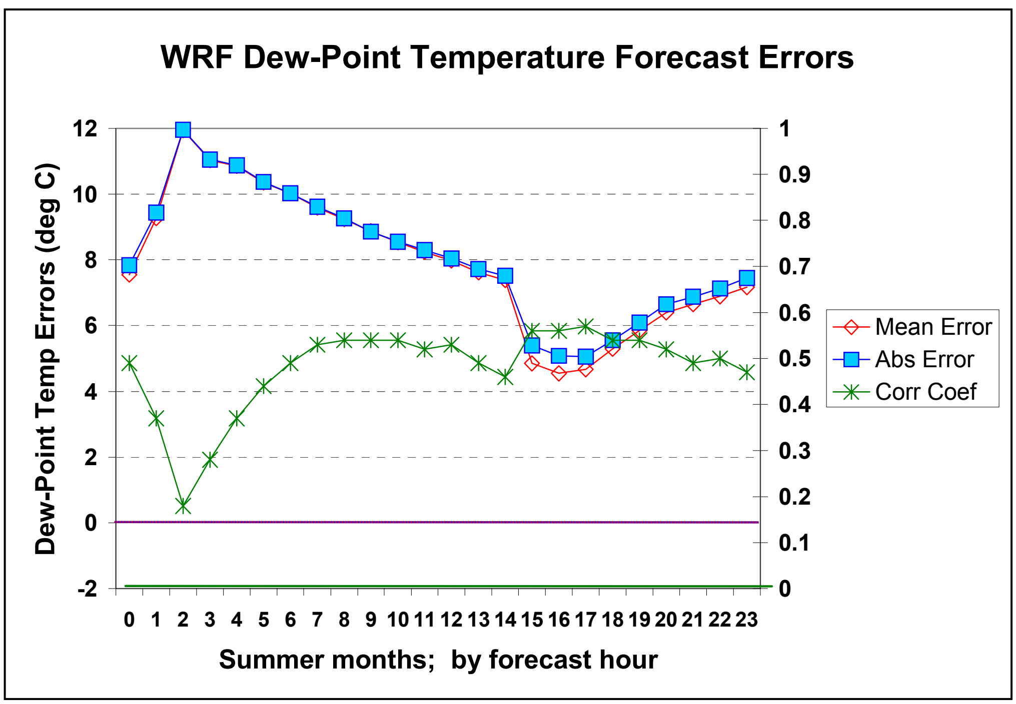

Figure 8. WRF dew-point temperature forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the summer model runs.

3.3 Relative Humidity Forecast Errors

The average relative humidity forecast errors are summarized in table 3.

Table 3. Average relative humidity errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (%)	-1	-5	16	5	21
Absolute Error (%)	15	17	19	16	22
RMSE (%)	19	22	23	22	27
Correlation Coefficient	.49	.43	.63	.31	.68
Number of Points	58000	54000	72000	55000	75000

As can be deduced from the substantial warm bias in the dew-point temperature forecasts, the WRF relative humidity forecasts are usually too high. The exception is forecast hours 17-23 in the winter months, which show a bias for the relative humidity forecasts to be between 0 and 10 °C too low. The winter MM5 forecasts show this slight low bias throughout all the forecast hours, with a somewhat stronger high bias for the summer forecast hours.

3.4 Wind Component Forecast Errors

The average *u*-wind component forecast errors are summarized in table 4.

Table 4. Average *u*-wind component errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (m/s)	0.3	0.5	0.1	0.6	0.1
Absolute Error(m/s)	1.8	1.6	2.2	1.6	1.8
RMSE (m/s)	2.7	2.4	3.1	2.5	2.6
Correlation Coefficient	.32	.36	.20	.36	.29
Number of Points	51000	42000	63000	42000	63000

The average *v*-wind component forecast errors are summarized in table 5.

Table 5. Average *v*-wind component errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (m/s)	0.1	0.7	0.9	0.4	0.4
Absolute Error(m/s)	2.0	2.3	2.5	2.1	2.0
RMSE (m/s)	2.8	3.2	3.3	3.0	2.8
Correlation Coefficient	.52	.44	.42	.47	.51
Number of Points	51000	42000	63000	42000	63000

It is not unusual for wind component correlation coefficients to be less than 0.5. The northern Utah area used for these forecasts contains large topographical variations over short horizontal distances, resulting in very localized wind flow effects that were difficult for the WRF and MM5 regional models to replicate.

3.5 Wind Speed Forecast Errors

The average wind speed forecast errors are summarized in table 6.

Table 6. Average wind speed errors.

	MM5	MM5		WRF	
	Winter 2003	**Winter** 2004	**Summer** 2003	**Winter** 2004	**Summer** 2003
Mean Error (m/s)	0.3	1.3	0.6	1.1	-0.1
Absolute Error (m/s)	1.8	2.0	2.1	2.0	1.8
RMSE (m/s)	2.4	2.7	2.7	2.7	2.3
Correlation Coefficient	.44	.41	.24	.41	.30
Number of Points	52000	43000	64000	43000	65000

The average wind speed absolute errors are close to 2 m/s for both models and both seasons. Although this error is not particularly large, the correlation coefficients don't indicate a significant amount of skill. The average monthly error did not vary for the two months within each seasonal category. The WRF forecasts for the winter months showed a higher wind speed bias and absolute error in the later forecast hours (fig. 9). On the other hand, the WRF forecasts for the summer months included a low bias for hours 0-5 and 17-23 (fig. 10). The MM5 wind

speed forecasts for the summer months also had a low bias for hours 18-23, but demonstrated a pronounced high bias during the nighttime forecast hours 3-15 (fig. 11).

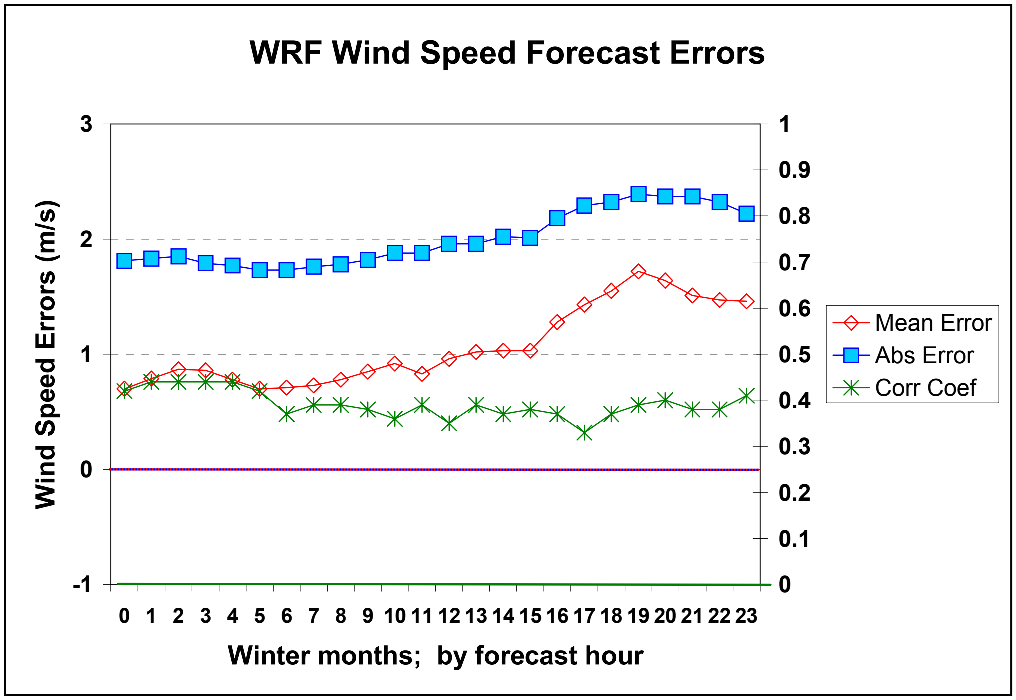

Figure 9. WRF wind speed forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the winter model runs.

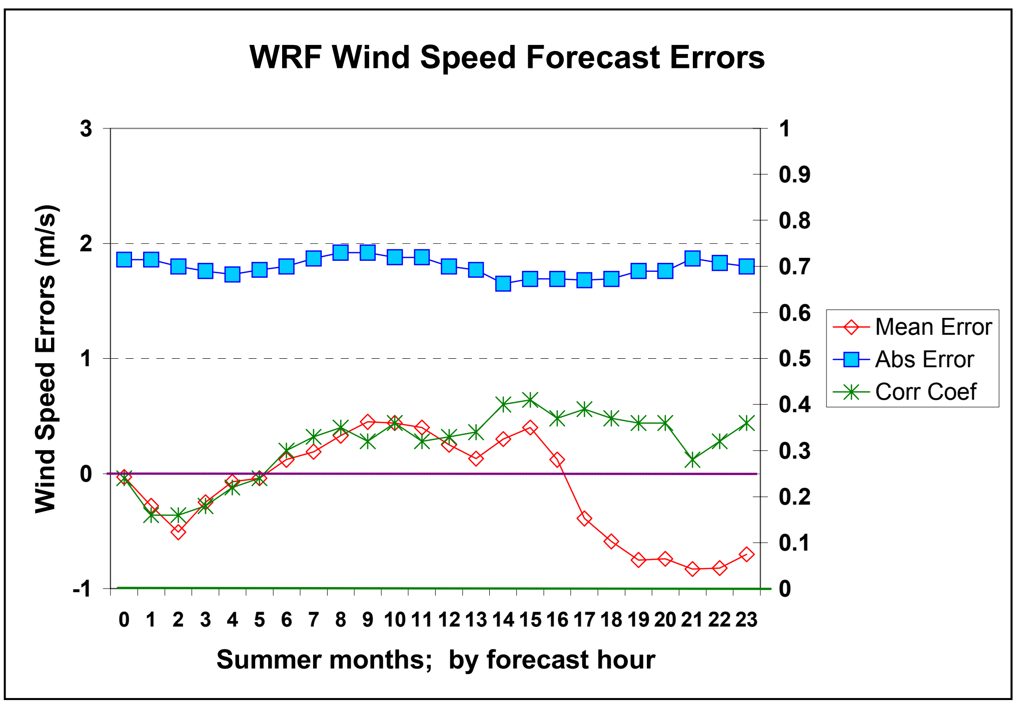

Figure 10. WRF wind speed forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the summer model runs.

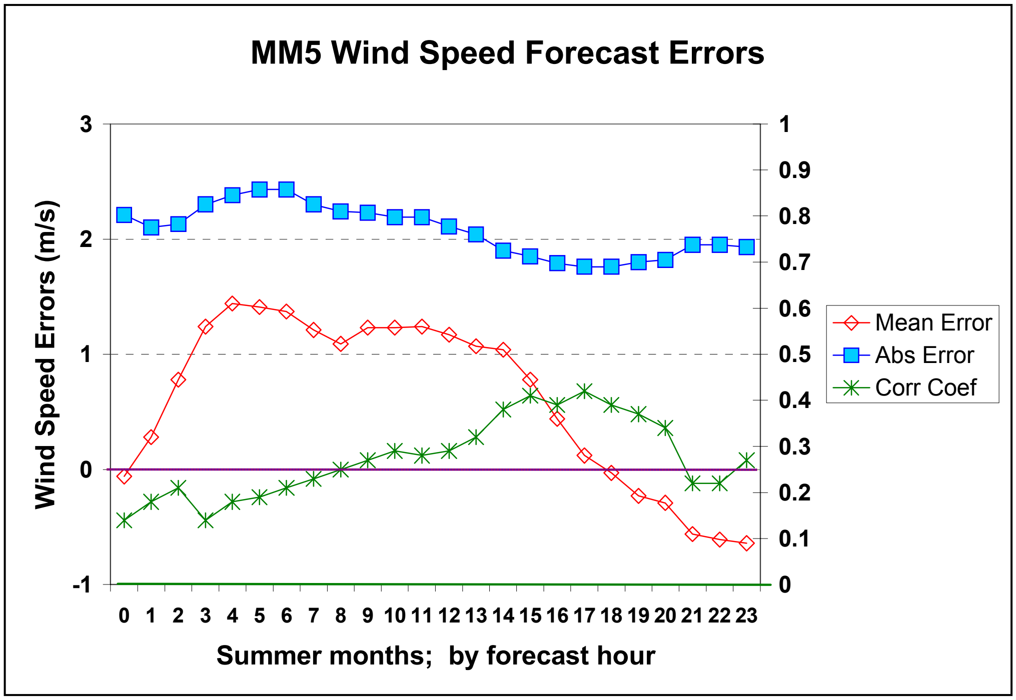

Figure 11. MM5 wind speed forecast errors (left axis) and correlation coefficients (right axis) by forecast hour for the summer model runs.

3.6 Wind Direction Forecast Errors

The average wind direction forecast errors are summarized in table 7.

Table 7. Average wind direction errors.

	MM5	MM5		WRF	
	Winter 2003	Winter 2004	Summer 2003	Winter 2004	Summer 2003
Absolute Error (º)	51	49	58	47	51
RMS Vector Error (m/s)	3.9	3.9	4.5	3.9	3.8
Number of Points	51000	42000	63000	42000	63000

NOTE: RMS = root mean square

The average wind direction errors generally fell between 50° and 60°, with the MM5 winter errors equivalent to those from the previous winter. Slightly higher errors occurred in the MM5 forecasts, particularly in the early forecast hours valid during the evening and nighttime. The July MM5 forecasts contained the highest wind direction errors; however, there was little difference in WRF's performance for the individual months. The RMS vector errors did not exhibit much variation by forecast hour or season.

4. Conclusions

This report documents the average MM5 and WRF forecast errors for basic surface parameters found over 111 days (in July and August 2003 and January and February 2004) over northern Utah. The approximate ranges of absolute error values averaged over the two months within each season are summarized below:

- Temperature forecast errors: 3.0-3.5 °C
- Dew-point temperature forecast errors: 3.5-8.0 °C
- Relative humidity forecast errors: 15-20 percent
- Wind speed forecast errors: 2.0 m/s
- Wind direction forecast errors: 50-60°

These errors are generally higher than would be desired in an operational weather forecast. Cases with very low wind speeds were not excluded in the statistics, which resulted in lower average wind speed forecast errors, but also contributed to higher wind direction errors based on the inclusion of light and variable wind situations.

Some additional analyses of these model forecast outputs will be performed to consider the model results at specific station locations. However, the primary emphasis will shift to running and evaluating using a newer, nested version of the WRF model.

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Acronyms

GFS	Global Forecast System
MM5	Pennsylvania State University/NCAR Mesoscale Model Version 5
NCAR	National Center for Atmospheric Research
RMS	root mean square
RMSE	root mean square error
WRF	Weather Research and Forecast

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